Tracking animal movements using stable isotopes

Keith A. Hobson
Isotopes as endogenous markers

- $^{12}$C
- $^{13}$C
- $^{14}$N
- $^{15}$N
- $^{32}$S
- $^{34}$S
- $^{16}$O
- $^{18}$O
- $^{1}$H
- $^{2}$H

δ$^{13}$C (‰)
δ$^{15}$N (‰)
δ$^{34}$S (‰)
δ$^{18}$O (‰)
δD (‰)
The basic principles of trophic level and source determinations

Primary Production

Herbivore

Respiration ($^{12}\text{C}$)

Excretion ($^{14}\text{N}$)

$\delta X$

Primary Production

$\Delta \delta_2$

$\Delta \delta_1$

$\delta X$
Choice of tissue …..
Metabolic routing: where does the element come from in your isotopic measurements?...

DIET

Protein

δD, δ^{15}N, δ^{13}C, δ^{34}S

Lipid

δD, δ^{13}C

Carb.

δ^{13}C

CONSUMER

Protein

Lipid

CO₂

δ^{13}C

H₂O
Isotopic discrimination and elemental turnover ....
Stable-N isotope discrimination (non herbivores)

King Penguin
Rockhopper Penguin
Ring-billed Gull
Great Skua
Peregrine Falcon
Garden Warbler

Humboldt’s Penguin
King Penguin
Rockhopper Penguin
Common Cormorant
European Shag
Ring-billed Gull
Black-tailed Gull
Great Skua
Nankeen Night Heron
Great White Egret
Grey Heron
Scarlet Ibis
White Ibis
Flamingo
Peregrine Falcon
Garden Warbler

High protein diets:

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$\Delta\delta^{13}C$</th>
<th>$\Delta\delta^{15}N$</th>
<th>$\Delta\delta^D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole Blood</td>
<td>1.5</td>
<td>2.9</td>
<td>?</td>
</tr>
<tr>
<td>Plasma</td>
<td>0.5</td>
<td>3.3</td>
<td>?</td>
</tr>
<tr>
<td>Muscle</td>
<td>1.9</td>
<td>3.1</td>
<td>?</td>
</tr>
<tr>
<td>Feather</td>
<td>2 to 3</td>
<td>3.8</td>
<td>-19 to -35</td>
</tr>
<tr>
<td>Claw</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Hobson and Bairlein *CJZ81*:1630-1635

Evans-Ogden et al *Auk* . 121:170-177
Milk to Soya

Mirón et al. 2006 J. Exp. Biol
Tissue turnover ....

\[ Y = ae^{-bt} + c \]

\[ T[1/2] = \frac{0.6932}{b} \]
Using a wind tunnel and isotopic dietary shifts to mimic migration

Max Planck Institute for Ornithology
Principles of isotopic tracking

- Animals move between unambiguous isotopically distinct “landscapes” and their tissues retain this information.
- Information “time window” depends on tissue chosen.
- Physiological aspects of movement and migration are understood in terms of turnover, metabolic routing etc.
The isotopic clock and movement

\[ \delta X \text{ (per mil)} \]

\[ \text{Time (days)} \]

Biome 2

Tissue 1

Tissue 2

Biome 1

\[ t_1', t_2', t_1, t_2 \]
Forensic applications are broad:
Some avian applications:
1. Game bird management
2. Movement of contaminants
3. Disease tracking: Avian Influenza
4. Connectivity and stable isotope tracking

Idea from Webster et al. *TREE* 17:76-83
5. Seasonal interactions …
### N.A. avian band recoveries (1955-2000)

<table>
<thead>
<tr>
<th>Species</th>
<th>Banded</th>
<th>recap</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada Goose</td>
<td>2,991,538</td>
<td>594,114</td>
<td>19.9</td>
</tr>
<tr>
<td>Mallard</td>
<td>5,935,960</td>
<td>878,704</td>
<td>14.8</td>
</tr>
<tr>
<td>N. Pintail</td>
<td>1,286,499</td>
<td>142,449</td>
<td>11.1</td>
</tr>
<tr>
<td>Merlin</td>
<td>26,308</td>
<td>674</td>
<td>2.6</td>
</tr>
<tr>
<td>Logg.shrike</td>
<td>22,897</td>
<td>196</td>
<td>0.86</td>
</tr>
<tr>
<td>Sp. sandpiper</td>
<td>13,673</td>
<td>79</td>
<td>0.58</td>
</tr>
<tr>
<td>R-t. hummingbird</td>
<td>54,218</td>
<td>53</td>
<td>0.10</td>
</tr>
<tr>
<td>Am. redstart</td>
<td>275,222</td>
<td>256</td>
<td>0.09</td>
</tr>
<tr>
<td>Myrtle warbler</td>
<td>824,013</td>
<td>704</td>
<td>0.09</td>
</tr>
<tr>
<td>W. flycatcher</td>
<td>28,194</td>
<td>20</td>
<td>0.07</td>
</tr>
<tr>
<td>Sw. thrush</td>
<td>371,313</td>
<td>251</td>
<td>0.07</td>
</tr>
</tbody>
</table>
So, banding doesn’t work, Can we use isoscapes?

- Terrestrial-marine ($\delta^{13}C$, $\delta^{15}N$ $\delta^{34}S$)
- Inshore-offshore ($\delta^{13}C$, $\delta^{34}S$, $\delta^{15}N$)
- C-3 vs. C-4, CAM ($\delta^{13}C$)
- Xeric vs. Mesic ($\delta^{13}C$, $\delta^{15}N$)
- Latitudinal/altitudinal gradients ($\delta D$, $\delta^{13}C$)
- Surficial geology (Sr, Pb, others)
From Schell et al. 2002
Mesic to xeric isotopic gradients help “locate” individuals and their tissues …
Barn swallows from Denmark are not all wintering in the same part of Africa …

Møller and Hobson (2004)
Population heterogeneity ....

<table>
<thead>
<tr>
<th>Tarsus length (mm)</th>
<th>Common</th>
<th>Rare</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.0</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>11.2</td>
<td>11.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Body mass (g)</th>
<th>Common</th>
<th>Rare</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(B)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T-cell response (mm)</th>
<th>Common</th>
<th>Rare</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Møller and Hobson (2004)
Using three stable isotopes to distinguish migrants from residents

Abstract: Effective management of Canada goose (Branta canadensis) requires a reliable method to determine the population affiliation of geese in the harvest. We determined if stable isotope analysis of feather tissue could distinguish between migrant and resident populations. We obtained feather samples of migrants from Atlantic population of Canada geese in northern Quebec near Ungava Bay, Canada. We grouped resident population Canada geese as coastal residents and inland residents according to the habitats where they were captured in New Jersey. We analyzed for isotopes of carbon (δ¹³C), nitrogen (δ¹⁵N), and sulfur (δ³⁴S). We found significant differences among migrants, coastal residents, and inland resident for all 3 isotopes. Combinations of isotopic ratios for the 3 elements resulted in unique patterns among groups of geese. We created the isotopic ratios into a discriminant analysis using collection site as the grouping variable (migrants, inland residents, and coastal residents). We found 2 significant functions that discriminated among the 3 groups 92% of the time. The first function accounted for 87% of the variance, and was highly influenced by the isotope ratios for carbon and sulfur. The results indicate that stable isotope analysis of primary羽毛 can provide a reliable means to discriminate between migratory and resident populations of Canada goose. Stable isotope analysis is a promising technique for identifying the breeding areas of Canada goose, but additional studies are needed to determine inherent variability over broad geographic areas.

Photo: Wyman Meinzer, USFWS
Wintering habitat determines arrival time on breeding grounds

Marra et al. (Science 1998)
Carry over effects ....

- High-quality habitat
  - Early arrival
    - Polygynous
    - Secure WP paternity
    - Increase total success
  - Late arrival
    - Monogamous
    - Lose WP paternity
    - Decrease total success

- Low-quality habitat
  - Non-breeding

Breeding season
Reudink et al. 2009

(a) claw δ¹³C (‰)

(b) proportion of offspring sired

(c) no. of genetic offspring fledged

(d) probability of polygyny

(e) total offspring fledged

Reudink et al. 2009
The BIG breakthrough: Using deuterium .....
The mean annual precipitation δD pattern:

Bowen et al. 2005
How does this pattern translate into bird feathers?

Hobson and Wassenaar *Oecologia* 109:142-148
North American Continental Pattern

Average Precip $\delta$D (per mil)

Feather $\delta$D (per mil)

-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0

-200 -180 -160 -140 -120 -100 -80 -60 -40 -20 0

-20 -40 -60 -80 -100 -120 -140 -160 -180

-160 -140 -120 -100 -80 -60 -40 -20 0

-160 -140 -120 -100 -80 -60 -40 -20 0

Songbirds
Ducks
For most birds ...
<table>
<thead>
<tr>
<th>Species</th>
<th>Equation</th>
<th>$r^2$</th>
<th>Model</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birds:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 species of North American songbird</td>
<td>$\delta D = -31 + 0.96 \delta D_p$</td>
<td>0.83</td>
<td>H</td>
<td>Hobson and Wassenaar (1997)</td>
</tr>
<tr>
<td>6 species of North American songbird</td>
<td>$\delta D = -25 + 0.96 \delta D_p$</td>
<td>0.88</td>
<td>B</td>
<td>Clark et al. (2006)</td>
</tr>
<tr>
<td>6 species of North American songbird</td>
<td>$\delta D = -19.4 + 1.07 \delta D_p$</td>
<td>0.86</td>
<td>B</td>
<td>Bowen et al. (2005)</td>
</tr>
<tr>
<td>Black-throated Blue Warbler</td>
<td>$\delta D = -51 + 0.58 \delta D_p$</td>
<td>0.86</td>
<td>CH</td>
<td>Chamberlain et al. (1997)</td>
</tr>
<tr>
<td>Red-winged blackbird</td>
<td>$\delta D = -27 + 1.13 \delta D_p$</td>
<td>0.83</td>
<td>H</td>
<td>Wassenaar and Hobson (2000)</td>
</tr>
<tr>
<td>Bicknell’s Thrush</td>
<td>$\delta D = -26 + 0.78 \delta D_p$</td>
<td>0.48</td>
<td>H</td>
<td>Hobson et al. (2001)</td>
</tr>
<tr>
<td>Wilson’s Warbler</td>
<td>$\delta D = -51.7 + 0.46 \delta D_p$</td>
<td>0.36</td>
<td>B</td>
<td>J. Kelly (unpublished)</td>
</tr>
<tr>
<td>Wilson’s Warbler</td>
<td>$\delta D = +14.47 + 1.41 \delta D_p$</td>
<td>0.91</td>
<td>M</td>
<td>Paxton et al. (2007)</td>
</tr>
<tr>
<td>Wilson’s Warbler</td>
<td>$\delta D = -21 + 0.75 \delta D_p$</td>
<td>0.48</td>
<td>M</td>
<td>Meehan et al. (2004)</td>
</tr>
<tr>
<td>Mountain Plover</td>
<td>$\delta D = +17.4 + 1.26 \delta D_p$</td>
<td>0.36</td>
<td>B</td>
<td>Wunder (2007)</td>
</tr>
<tr>
<td>23 species of European birds</td>
<td>$\delta D = -7.8 + 1.27 \delta D_p$</td>
<td>0.65</td>
<td>B</td>
<td>Hobson et al. (2004d)</td>
</tr>
<tr>
<td>23 species of European birds</td>
<td>$\delta D = -22.3 + 0.77 \delta D_p$</td>
<td>0.85</td>
<td>B</td>
<td>Bowen et al. (2005)</td>
</tr>
<tr>
<td>Cooper’s Hawk</td>
<td>$\delta D = -34 + 1.07 \delta D_p$</td>
<td>0.83</td>
<td>H</td>
<td>Meehan et al. (2001)</td>
</tr>
<tr>
<td>Inland generalist raptors</td>
<td>$\delta D = -40 + 0.62 \delta D_p$</td>
<td>0.59</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>Inland bird-eating raptor</td>
<td>$\delta D = -44.2 + 0.54 \delta D_p$</td>
<td>0.37</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>Coastal generalist raptors</td>
<td>$\delta D = -38.8 + 0.55 \delta D_p$</td>
<td>0.19</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>Coastal bird-eating raptors</td>
<td>$\delta D = -104.7 + 0.59 \delta D_p$</td>
<td>0.12</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>Non-coastal bird-eating raptors</td>
<td>$\delta D = -41.1 + 0.88 \delta D_p$</td>
<td>0.46</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>9 species of raptors</td>
<td>$\delta D = -52.2 + 0.28 \delta D_p$</td>
<td>0.09</td>
<td>H</td>
<td>Lott et al. (2003)</td>
</tr>
<tr>
<td>9 species of diurnal raptors</td>
<td>$\delta D = -37 + 0.66 \delta D_p$</td>
<td>0.51</td>
<td>M</td>
<td>Meehan et al. (2004)</td>
</tr>
<tr>
<td>Raptors in South Carolina</td>
<td>$\delta D = -25 + 0.75 \delta D_p$</td>
<td>0.18</td>
<td>M</td>
<td>Meehan et al. (2004)</td>
</tr>
<tr>
<td>Flammulated Owl</td>
<td>$\delta D = -8 + 0.95 \delta D_p$</td>
<td>0.66</td>
<td>M</td>
<td>Meehan et al. (2004)</td>
</tr>
<tr>
<td>12 species of raptors</td>
<td>$\delta D = -5.6 + 0.91 \delta D_p$</td>
<td>0.62</td>
<td>M</td>
<td>Lott and Smith (2006)</td>
</tr>
<tr>
<td>Scaup</td>
<td>$\delta D = -27.8 + 0.95 \delta D_p$</td>
<td>0.64</td>
<td>B</td>
<td>Clark et al. (2006)</td>
</tr>
<tr>
<td>Mallards and Northern Pintail</td>
<td>$\delta D = -57 + 0.835 \delta D_p$</td>
<td>0.56</td>
<td>M</td>
<td>Hebert and Wassenaar (2005)</td>
</tr>
<tr>
<td>Other animals:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deer collagen</td>
<td>$\delta D = 4 + 1.02 \delta D_p$</td>
<td>0.94</td>
<td>C</td>
<td>Cormie et al. (1994)</td>
</tr>
<tr>
<td>Hoary bat</td>
<td>$\delta D = -25 + 0.8 \delta D_p$</td>
<td>0.60</td>
<td>M</td>
<td>Cryan et al. (2004)</td>
</tr>
<tr>
<td>Monarch butterfly</td>
<td>$\delta D = -79 + 0.62 \delta D_p$</td>
<td>0.69</td>
<td>H</td>
<td>Hobson et al. (1999)</td>
</tr>
<tr>
<td>Beetle (chitin)</td>
<td>$\delta D = 33.2 + 1.60 \delta D_p$</td>
<td>0.74</td>
<td>B</td>
<td>Gröcke et al. (2006)</td>
</tr>
</tbody>
</table>
Using $\delta D$ to track Monarch migration ....
Two populations, one long distance journey ....
Previously, tagging was used:
Needle in a haystack?
How to create an isotopic base map?
Monarchs can be “grown” anywhere!
The basemap for the year of interest:
Origins: 50% of the population is produced in the US cornbelt:
Meteoric relationship preserved in Monarch Butterflies

\[ y = 7.951x - 123.948 \]

\[ R^2 = 0.936 \]
Other isotopic delineations of population structure ...

Rubenstein et al. (Science 2002)
“Leapfrog” migration revealed..

Kelly et al. (Oecologia 2002)
Altitudinal gradients are recorded in hummingbird feathers:

The feather isotopes follow large scale trajectories in precip $\delta D$

**Ecuador:**

$$\delta D_f = -25.6 + E(-0.014) \text{ -25 }^{\circ}/oo$$

**Global:**

$$\delta D_f = -22 + E(0.0224) \text{ -25 }^{\circ}/oo$$
Origins of hunter-killed Sandhill Cranes?
Toenails or feathers?

\[ Y = 11.1 + 1.05X \]

\[ r^2 = 0.62 \]
Combining isotope results with the isotope basemap GIS layer ....
Moving beyond the “map lookup” approach …..

- Propagate error associated with analytical measurement and geospatial models of δDp.
Converting to $\delta Dp$ units

$$\delta Dp = 24.92 + 1.04 \times \delta Df$$

RMA fit to known source birds
Within Site “Errors”

Calculate SD for each Site

Incorporates:
- analytical error
- individual heterogeneity
Observed Distribution of errors

![Bar chart showing frequency of within site SD errors]
Fit distribution to errors

MLE fit to Observed Errors

Gamma distribution
- shape = 7.156
- scale = 1.322
Propagate errors (simulation)

- 1000 simulations per measured $\delta D_f$ (in $\delta D_p$ units)

- Where:
  - Mean = measured $\delta D_p$ equivalent value of feather
  - SD drawn at random from estimated error distribution
Origins of Woodpigeons killed in France

Several distinct populations with specific migratory traits

- Long-range migrant (winter in southern range of Europe)
- Medium-range migrant (winter in France)
- Sedentary
Constraining Origins

\[ \delta Dp \]

High : -2.94
Low : -98.14
Constraining to Potential Range

Potential Range of Woodpigeon wintering in France
Constraint- Elevation
Reduced solution space - remove high elevation
GSD- for reduced range
Assignment of Origins

Map showing probability density for δD precip across Europe.
Limitations of the BBS for Boreal Birds
Yellow Warbler (Fall)

LMBO, BBO, LSLBO

TCBO, DMBO

Maritimes, Quebec, Ont.
West Nile Virus exposure in N. Cardinals

2002

2003
WNV in Gray Catbirds (2003)
For North Africa ...

Bowen et al., 2005
3-dimensional isoscape for trans-Saharan migrants ....

\[ \delta^{13}C \]

\[ \delta^{15}N \]

\[ \delta D \]
What about Asia?
3 useable zones?
Of use for N-S movements
Mean = -91.6639
Std. Dev. = 39.68184
N = 119
Freshwater isoscapes (δD)?
Scaling down: Can we use more local isoscapes?
Local-scale isoscapes: Nebraska
Here is a “deer isoscape”

With Larkin Powell
Travels of an unfortunate cougar

**A**

- **Claw tip** (Old time)
- **Time**
- **Claw root** (Recent time)

**B**

- **δD (%)**
- **δ¹³C (%)**
Human Hair

Ehleringer et al. (PNAS 2008)
Fig. 3. Geographic Information System-generated maps of the predicted average H isotope ratios ($\delta^{2}H$) (A) and average O isotope ratios ($\delta^{18}O$) (B) of human scalp hair across the coterminous United States.

Fig. 4. Time sequence plots of the H ($\delta^{2}H$) and O ($\delta^{18}O$) isotope ratios of human scalp hair along a basal-to-tip transect for an individual that moved from Beijing, China, to Salt Lake City, Utah.
Figure 10. A plot of the carbon and oxygen isotope data measured from hair from the Sierra Nevada murder victim as a function of time prior to the victim's death with three iso-locations marked. Time was calculated based on an average growth rate of 0.4 mm/day. Data are 3-point running means. Iso-locations are those regions where it is suggested that the victim had resided for a period of time.
Figure 6. The predicted distribution of oxygen isotope ratios of carbonates in enamel from human teeth across the contiguous USA.
Trace element/heavy isotope

Compound specific Mass spectrometry